ECE4902 C2012 Lab 3

Qualitative MOSFET V-I Characteristic
SPICE Parameter Extraction using MOSFET Current Mirror

The purpose of this lab is for you to make both qualitative observations and quantitative measurements of MOSFET behavior in different operating regions. Upon completion of this lab you should be able to:

- Recognize the V_{DS}-I_D characteristic of an N-channel MOSFET
- Recognize the triode and saturation regions of operation in the V_{DS}-I_D characteristic
- Have an idea of how small the "small V_{DS}" requirement is for resistive behavior of the drain-source channel
- Compare drain-source channel resistance calculated from the V_{DS}-I_D plot to resistance measurements made using the DVM in Lab 2
- Recognize the compliance voltage, the smallest V_{DS} for which the drain-source channel looks like a current source in the saturation region
- Recognize the finite output resistance in the saturation region that makes the drain-source channel look like a nonideal current source
- Distinguish between the "true" resistance R_{on} of the drain-source channel in the resistive part of the triode region, and the small-signal drain output resistance r_o in the saturation region
- Extract SPICE parameters VTO (threshold voltage) and UO (mobility) for both P-channel and N-channel MOSFETs in the saturation region of operation.
- Recognize the current mirror configuration, and the voltage range over which the current mirror behavior applies.
- Determine the channel length modulation parameter λ and relate to the substrate doping NSUB.

Lab Exercise

In lecture, we showed how the MOSFET channel behaves differently as the channel (drain-source voltage V_{DS} increases:

Small V_{DS}	linear V_{DS}-I_D relationship (model as resistance R_{on})
Medium $V_{DS} < V_{GS} - V_{TH}$	nonlinear triode relationship
Large $V_{DS} > V_{GS} - V_{TH}$	approximately constant current determined (mostly) by V_{GS}

In the first part of this lab exercise, you will build a circuit that provides a plot of drain current I_D vs drain-source voltage V_{DS} on the oscilloscope. By sweeping V_{DS} over a range of 0V to +5V, you will see the output characteristic in the triode and saturation regions.

In the second part of the lab exercise, you will build up the same plot from measured data points to determine SPICE parameters for N-channel and P-channel MOSFETs.

Qualitative MOSFET V-I Characteristic

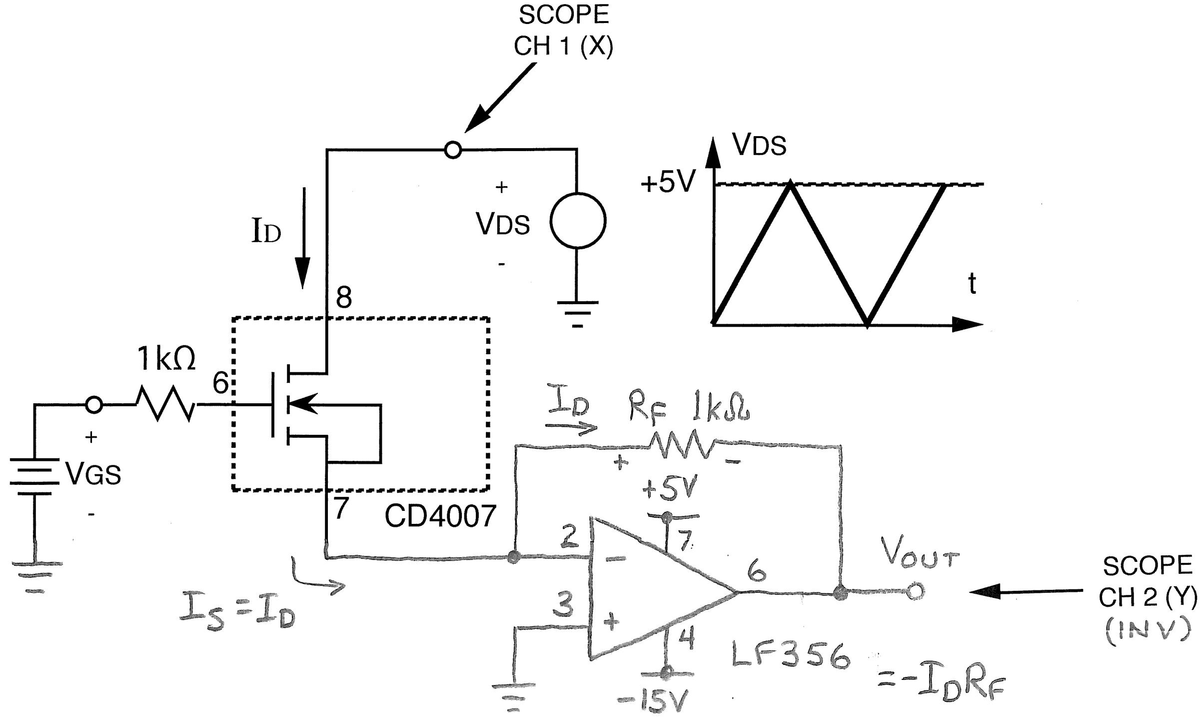


Fig. L3-1.

L3-1. Build the circuit in Fig. L3-1. The MOSFET gate-source voltage will be maintained at a constant value while the drain voltage is swept from 0V to 5V. From Kirchoff's law for the MOSFET the current I_S at the source must equal the current I_D at the drain, since the gate current and substrate current are both zero. The LF356 is configured as a transimpedance amplifier which keeps the source of the MOSFET (CD4007 pin 7) at zero volts while allowing the current to flow in the feedback resistor R_F. The output of the transimpedance amplifier is given by $V_{OUT} = -I_D R_F$, so the oscilloscope CH2 voltage will be $V_{OUT} = -1k\Omega \cdot I_D$. Therefore, if the CH 2 scale is set to 1V/div, and the "Invert" function is used on scope CH 2, then the scope display will be equivalent to a current measurement of I_D at 1mA/V.

L3-2. Configure the function generator to set up the input V_{DS}: adjust the frequency to around 100Hz; adjust the offset and amplitude to get a 0 to +5V triangle wave.

L3-3. Use one of the bench power supply adjustable outputs to set up V_{GS} as a DC source. Adjust the supply to provide a value of V_{GS} equal to about 2V greater than your threshold voltage from Lab 2 (equivalently, $V_{GS} - V_{TH} \approx 2V$). The display on the power supply is not too accurate so you might want to dedicate the DVM to measuring the value of V_{GS}.

L3-4. Configure the oscilloscope. With both channels set to DC coupling, set the CH1 scale to 1V/div and the CH2 scale to 0.2V/div. In the DISPLAY menu, set up scope for an X-Y display. This will display CH1 on the X-axis and CH2 on the Y-axis. To correctly position the origin of the X-Y plot, use the vertical menu to ground both channels, and adjust position so the 0-0 dot is at lower left corner of the screen.

L3-5. Now (making sure that both channels are set for DC coupling), you should see a plot similar to Fig. L3-2 (with some noise!). $I_{D(T\text{-}S)}$ is the drain current at the boundary between the Triode and Saturation regions. Adjust V_{GS} for a current $I_{D(T\text{-}S)}$ = 1 mA, which should be 5 vertical divisions on the scope. Record the following:

L3-6: Using the DVM, measure the value of the applied V_{GS} .

L3-7. From the oscilloscope plot, choose a point on the V-I plot near the origin ("near" = in the resistive part of the triode region). Measure $\Delta I_{D(T)}$ and $\Delta V_{DS(T)}$ and determine the "on" resistance $R_{on}=\Delta V_{DS(T)}/\Delta I_{D(T)}$.

L3-8. From the oscilloscope plot, measure the compliance voltage $V_{DS(T\text{-}S)}$, which can be viewed as:
- the voltage at which the MOSFET makes the transition from saturation region to triode region, or
- the minimum V_{DS} for which the MOSFET still "looks like" a current source.

Note that this determination is a little fuzzy from a scope plot; you would need to take lots of data and do some curve fitting to determine the boundary more precisely. We are just looking for a qualitative indication here, so precision for this part isn't important yet.

L3-9. From the oscilloscope plot, determine the drain current $I_{D(T\text{-}S)}$ at the boundary between the triode and saturation regions (at which the channel is just pinching off).

L3-10. From the oscilloscope plot, determine the slope of the output characteristic in the saturation region. As V_{DS} varies over a range of $\Delta V_{DS(S)}$ from $V_{DS(T\text{-}S)}$ to +5V, the output drain current will vary over a range of $\Delta I_{D(S)}$. The slope $\Delta I_{D(S)}/\Delta V_{DS(S)}$ in μA/V is a measure of how well the MOSFET behaves as a current source. For an ideal current source, the slope would be zero since the current should be independent of applied voltage for an ideal current source. However, due to channel length modulation, the current does increase slightly as V_{DS} increases. Also determine the inverse of this slope, which is the small signal output resistance $r_o = \Delta V_{DS(S)} / \Delta I_{D(S)}$.

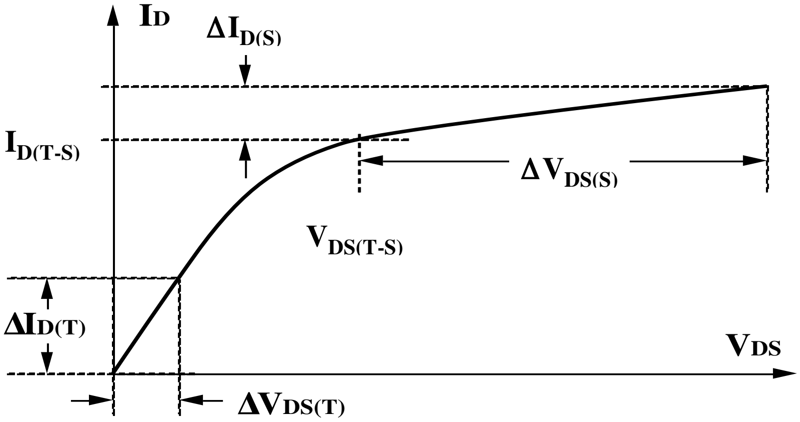


Fig. L3-2.

SPICE Parameter Extraction using MOSFET Current Mirror

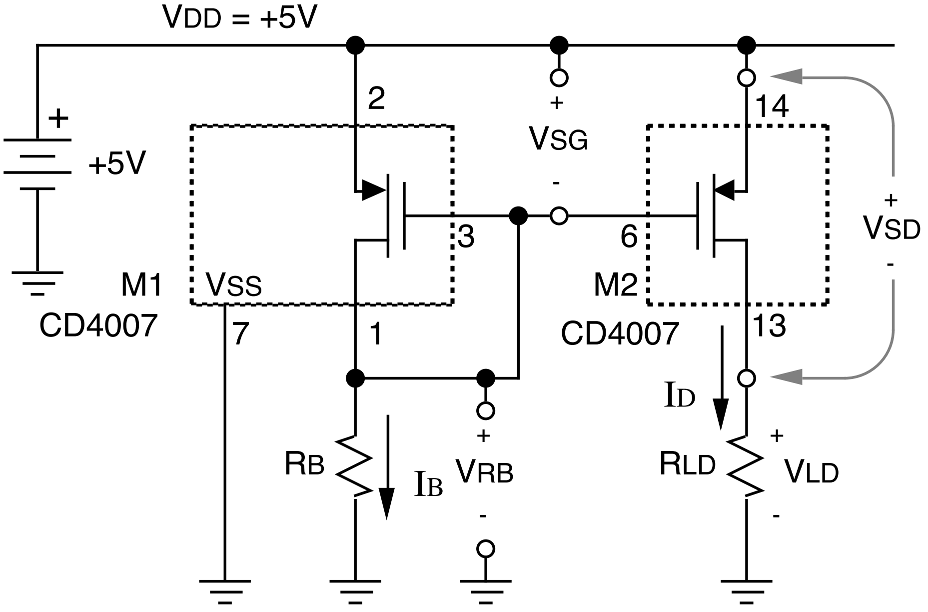


Figure L3-3.

CIRCUIT: MOSFET CURRENT MIRROR (P-CHANNEL)

The circuit shown in Figure L3-3 is referred to as a "current mirror," since the current I_D in transistor M2 ideally duplicates ("mirrors") the current I_B in M1. The current in resistor R_B is

$$I_B = \frac{5V - V_{SG}}{R_B} \qquad [3\text{-}1]$$

Since the current into both gates is zero, by KCL the drain current of M1 must be equal to I_B. The "mirroring" action occurs because the circuit configuration forces M1 and M2 to have the same gate-source voltage V_{SG}. Since transistors M1 and M2 are matched (fabricated next to each other on the same IC silicon), if they have the same V_{SG} and are both operating in the saturation region, they will (ideally) have the same drain current, so $I_D = I_B$. Note that this argument doesn't depend on the square law model, just on matching considerations - a recurring theme in IC design.

The configuration of MOSFET M1, with gate and drain tied together, is often referred to as a "diode-connected" MOSFET configuration. This is because the MOSFET becomes essentially a two-terminal device which only conducts current when the voltage exceeds the threshold voltage (similar to the diode, which only conducts when the diode voltage exceeds ≈ 0.7V). Note that a diode-connected MOSFET must be in the saturation region, since the connection of gate to drain forces V_{GD}=0, which ensures the MOSFET channel is pinched off at the drain end.

In this lab, you will be using different values of R_B to set the current in the diode connected MOSFET. To solve exactly for V_{SG} and R_B in a design problem, we would use the square law model equation which relates I_B and V_{SG} for the P-channel device:

$$I_B = \frac{\mu_p C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_{TH}\right)^2 \qquad [3\text{-}2]$$

for I_B into Eq. [3-1] and solve the resulting quadratic in V_{SG}. For the purposes of this lab, however, we'll approach things from a measurement point of view. For the CD4007, you already know C_{ox} (from your capacitance measurements in Lab 2) and it is also known

W_p/L_p=900μm/10μm. By measuring I_B and V_{SG}, the only remaining unknowns in Eq. [3-2] are the threshold voltage VTH and the hole mobility μ_p. You will use two different values of R_B, measure I_B and V_{SG}, and use the results to solve for VTH and the hole mobility μ_p.

Note that there is no minus sign in Eq. [3-2], unlike the Razavi text eq. (2.15) for saturation current in the PMOS device. The reason is that positive current I_B is defined as flowing out of the drain for the PMOS device on Figure L3-3).

ID-VDS CHARACTERISTICS FOR VARIOUS VALUES OF VGS (P-CHANNEL)

L3-11. Build the circuit of Fig. L3-3. Be sure to completely disconnect the wiring to the CD4007 from the previous circuit! For R_B, use 5.1kΩ and 51kΩ. Be sure to measure the actual value of each R_B, and record it in Table L3-1.

L3-12. For each value of R_B, measure the associated value of V_{GS}. Record this value in Table L3–1. Also, measure the voltage drop V_{RB} across R_B, calculate current I_B using the value of R_B from part L3-11, and record the value of I_B in Table L3-1.

L3-13. For each value of R_B, substitute the different values of R_{LD} indicated in Table L3-1. Measure the voltage drop V_{LD} across resistor R_{LD}, and also measure the source-drain voltage V_{SD} and the measured drain current I_D. Record the data in Table L5-1. For each value of R_{LD}, calculate the current $I_D = V_{LD}/R_{LD}$. If you'd like to save time, skip the values with shaded-out boxes in the table; those data points don't provide that much additional information.

Table L3-1. P-channel MOSFET data

R_B = 5.1kΩ (NOMINAL)

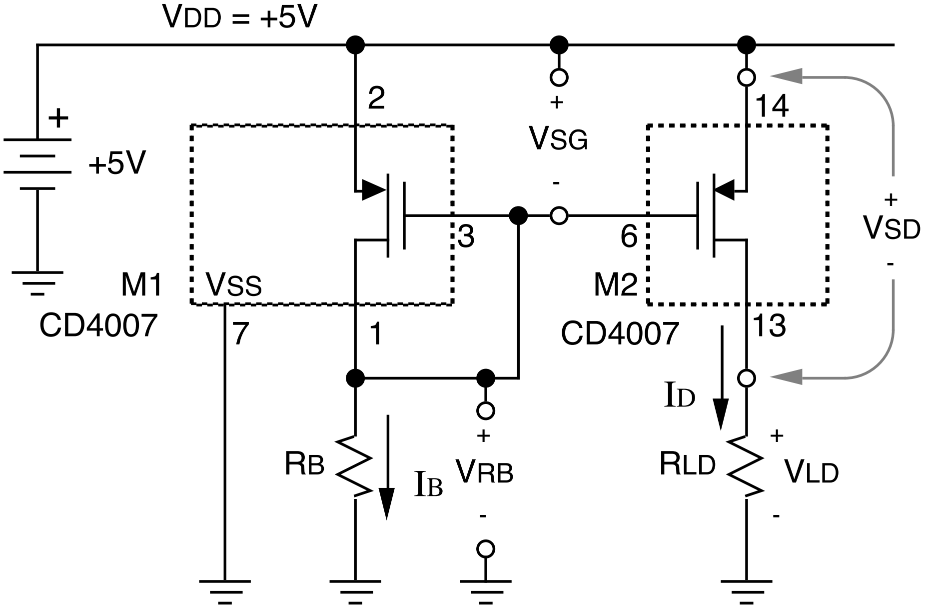
R_B = ________ MEASURED
V_{GS} = ________ MEASURED
V_{RB} = ________ MEASURED
I_B = ________ CALCULATED $I_B = V_B / R_B$

	MEASURED		CALCULATED $I_D = V_{LD} / R_{LD}$
R_{LD}	V_{LD}	V_{DS}	I_D
1 kΩ			
2 kΩ			
3 kΩ			
5.1 kΩ			
10 kΩ			
20 kΩ			
30 kΩ			
51 kΩ			
100 kΩ	▨	▨	▨
200 kΩ	▨	▨	▨
300 kΩ	▨	▨	▨

R_B = 51kΩ (NOMINAL)

R_B = ________ MEASURED
V_{GS} = ________ MEASURED
V_{RB} = ________ MEASURED
I_B = ________ CALCULATED $I_B = V_B / R_B$

	MEASURED		CALCULATED $I_D = V_{LD} / R_{LD}$
R_{LD}	V_{LD}	V_{DS}	I_D
1 kΩ	▨	▨	▨
2 kΩ	▨	▨	▨
3 kΩ	▨	▨	▨
5.1 kΩ			
10 kΩ			
20 kΩ			
30 kΩ			
51 kΩ			
100 kΩ			
200 kΩ			
300 kΩ			



VDD = +5V
+
+5V
2
+
VSG
-
14
+
VSD
-
3
6
M1
VSS
M2
CD4007
7
1
CD4007
13
ID
+
RB
IB
VRB
-
RLD
+
VLD
-

Figure L3-3.

ID-VDS CHARACTERISTICS FOR VARIOUS VALUES OF VGS (N-CHANNEL)

L3-14. Build the circuit of Fig. L3-4. Be sure to completely disconnect the wiring to the CD4007 from the previous circuit! For R_B, use 5.1kΩ and 51kΩ. Be sure to measure the actual value of each R_B, and record it in Table L3-2.

L3-15. For each value of R_B, measure the associated value of V_{GS}. Record this value in Table L3–2. Also, measure the voltage drop V_{RB} across R_B, calculate current I_B using the value of R_B from part L3-14, and record the value of I_B in Table L3-2.

L3-16. For each value of R_B, substitute the different values of R_{LD} indicated in Table L3-2. Measure the voltage drop V_{LD} across resistor R_{LD}, and also measure the source-drain voltage V_{SD} and the measured drain current I_D. Record the data in Table L3-2. For each value of R_{LD}, calculate the current $I_D = V_{LD}/R_{LD}$. If you'd like to save time, skip the values with shaded-out boxes in the table; those data points don't provide that much additional information.

Table L3-2. N-channel MOSFET data

R_B = 5.1kΩ (NOMINAL)

R_B = ________

V_{GS} = ________ $\Big\}$ MEASURED

V_{RB} = ________

I_B = ________ $\Big\}$ CALCULATED $I_B = V_B / R_B$

R_{LD}	MEASURED V_{LD}	MEASURED V_{DS}	CALCULATED $I_D = V_{LD} / R_{LD}$ I_D
1 kΩ			
2 kΩ			
3 kΩ			
5.1 kΩ			
10 kΩ			
20 kΩ			
30 kΩ			
51 kΩ			
100 kΩ	▨	▨	▨
200 kΩ	▨	▨	▨
300 kΩ	▨	▨	▨

R_B = 51kΩ (NOMINAL)

R_B = ________

V_{GS} = ________ $\Big\}$ MEASURED

V_{RB} = ________

I_B = ________ $\Big\}$ CALCULATED $I_B = V_B / R_B$

R_{LD}	MEASURED V_{LD}	MEASURED V_{DS}	CALCULATED $I_D = V_{LD} / R_{LD}$ I_D
1 kΩ	▨	▨	▨
2 kΩ	▨	▨	▨
3 kΩ	▨	▨	▨
5.1 kΩ			
10 kΩ			
20 kΩ			
30 kΩ			
51 kΩ			
100 kΩ			
200 kΩ			
300 kΩ			

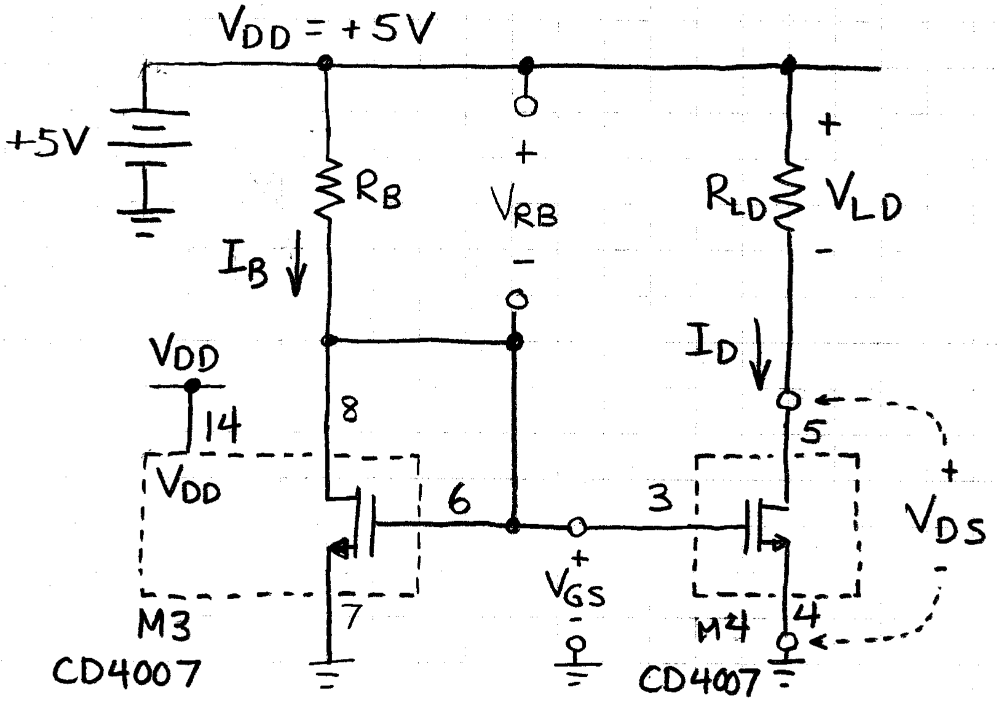

VDD = +5V
+5V
RB
IB
+
VRB
−
RLD
+
VLD
−
ID
VDD
14
VDD
8
6
3
5
+
VDS
−
+
VGS
−
7
4
M3
CD4007
M4
CD4007

Figure L3-4.

Lab Writeup

Qualitative MOSFET V-I Characteristic

W3-1. Record the output characteristic I_D as a function of V_{DS} from the oscilloscope plot. Label the triode and saturation regions on the plot.

W3-2. Compare the resistance in the linear part of the triode region (measured in part L3-7) to the resistance you measured with the DVM in Lab 2. Use the closest data point to your measured value of V_{GS} from part L3-6, or interpolate on your plot of results from Lab 2. Also compare to the result of the R_{on} equation using your extracted values of μ_n, C_{ox}, V_{TH}, the known $W_n/L_n = 350\mu m/10\mu m$, and the value of V_{GS} measured in L3-6.

W3-3. Compare the measured value of the compliance voltage $V_{DS(T-S)}$ from L3-8 with the expected value of $V_{GS} - V_{TH}$. There may be some error given the fuzzy nature of the measurement.

W3-4. Compare the measured current at pinchoff $I_{D(T-S)}$ from L3-9 with the value predicted by the square law.

W3-5. Record the slope from part L3-10, and also calculate 1/slope, the output resistance of the current source. You'll come back to this when you compare with the quantitative treatment of channel length modulation in W3-10 and W3-11.

ID-VDS CHARACTERISTICS FOR VARIOUS VALUES OF VGS (P-CHANNEL)

W3-6. From your measured values of V_{SG} and I_B in table L3-1, determine threshold voltage V_{TH} and the hole mobility μ_p. Compare to the values extracted in the triode region from Lab 2. If there is a difference, don't panic - there are oversimplifications in the basic square law model that result in different values being extracted in the saturation vs. triode regions.

W3-7. For each value of R_B, plot I_D as a function of V_{SD}. For each plot, identify the saturation region and triode region of operation. You may have to use some creative “filling in” of the space between data points, since the time limitation of the lab only allows for the taking of fewer data points than we’d like. In particular, there may not be enough resolution to say definitively where the saturation-triode boundary is.

ID-VDS CHARACTERISTICS FOR VARIOUS VALUES OF VGS (N-CHANNEL)

W3-8. From your measured values of V_{GS} and I_B in table L3-2, determine threshold voltage V_{TH} and the electron mobility μ_n. Compare to the values extracted in the triode region from Lab 2. Again, if there is a difference, don't panic - there are oversimplifications in the square law model that result in different values being extracted in the saturation vs. triode regions.

W3-9. As in W3-7, for each value of R_B, plot I_D as a function of V_{DS}. For each plot, identify the saturation region and triode region of operation.

CHANNEL LENGTH MODULATION

The general shape of your plots from W3-7 and W3-9 should look something like figure L3-5 on the next page: In reality, the drain current shows a slight dependence on drain voltage. This means the output is not a perfect current source in the saturation region, and therefore the current matching of the "mirror" isn't perfect. The primary reason is channel-length modulation, which is discussed in your text in pp. 25-26, and we will talk about more in class.

P-CHANNEL MOSFET

W3-10. From your data in W3-7, select a range of points in the saturation region and determine the value of r_o, the small-signal output resistance of the current mirror. Use the procedure shown in the figure. You will get different r_o values for the two different currents.

W3-11. From your values of r_o, determine the channel length modulation parameter λ_p using

$$\lambda = \frac{1}{I_D \cdot r_o}$$

where I_D is the value of drain current extrapolated back to the I_D axis as shown in the figure. Compute λ for each of the two cases of current; the value of λ should be approximately independent of I_D. Use the average of the two values as λ_p, the channel length modulation parameter for the P-channel MOSFET.

N-CHANNEL MOSFET

W3-10. Repeat the procedure in W3-10 and W3-11 to determine λ_n, the channel length modulation parameter for the N-channel MOSFET. Note that in general λ_p and λ_n will not be equal!

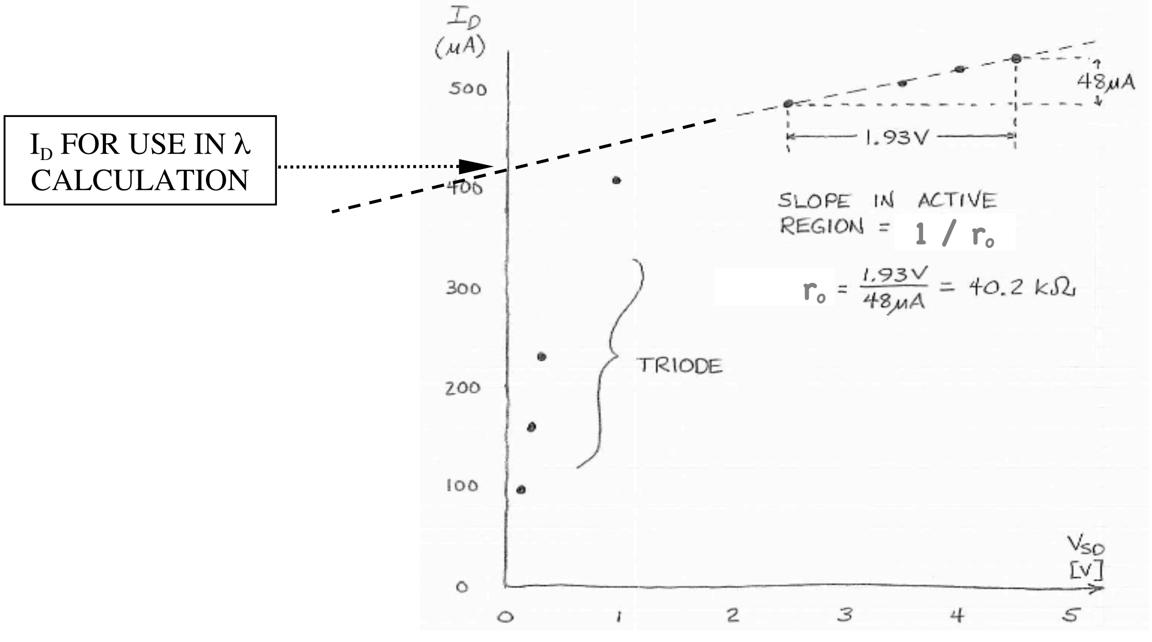


Figure L3-5.

Simulation

Parameters VTO, UO, NSUB

S3-1. With help from the Lab 3 simulation page

http://ece.wpi.edu/~mcneill/4902/labs/lab3/Lab3.html

perform a DC simulation to add parameters to your models for NMOS and PMOS devices that will give the same I_D-V_{DS} plots as you measured in the lab. You will keep the same TOX from your lab 1 results, and add the following parameters:

VTO	Threshold voltage
UO	Low E field mobility
NSUB	Substrate doping

Use the VTO values you extracted from the R_{on} measurements in lab 2. The procedure for extracting the UO and NSUB parameters is in a link on the Lab 3 web page.

Include a plot of the DC sweep results in the lab writeup you hand in.